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Investigation of Subterranean Fuel Vapor Extraction and Destruction Using a Diesel Engine

INTERIM REPORT
TFLRF No. 359

by
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Technology Transfer Division
Brooks Air Force Base
San Antonio, Texas

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The objective of this project was to determine the feasibility of using a diesel engine as a means of fuel vapor extraction and destruction at underground contamination sites. The first priority was to determine if fuel vapors introduced into the engine via the intake air stream could be burned satisfactorily. An engine operated in this manner functions similarly to a dual-fuel natural gas/diesel unit, using liquid fuel as a pilot to ignite the gas-air mixture. A major concern with this concept is the possibility that fuel vapors pre-mixed with the intake air may be prone to detonation in a high compression diesel engine, therefore causing destructive knock. Another concern is whether the engine will run properly without using an excessive amount of supplemental liquid fuel, which then reduces the vapor extraction capability and overall efficiency of the system. Therefore, the main focus of this initial test phase was on combustion performance and pilot fuel requirements versus gaseous fuel consumption.

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U.S. Army TARDEC Fuels and Lubricants
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EXECUTIVE SUMMARY

Problems and Objectives: Environmental and health hazards posed by soil contamination as the result of underground fuel tank leakage and spillage at U.S. Air Force bases has created a need for cost effective methods of removing volatile and combustible compounds from subterranean soil. Following removal of as much liquid-state contaminant as possible from a site, the next step in the clean-up process is to further remove contaminant in gaseous form as it evaporates from the saturated soil. One method employed is to bore a well, insert a pipe into the contaminated soil and route the vapors into the intake air of a running engine for combustion.

Current engines being used for this task are automotive type, spark-ignited models that utilize propane or natural gas as a supplemental fuel source during startup and lean vapor conditions. The question was raised as to whether the same function could be provided by a compression-ignition (CI) diesel engine and perhaps gain an increase in efficiency, durability and reliability. The objective of this project was to determine the feasibility of this concept.

Importance of Project: The continuous operation of an engine for this purpose can result in significant maintenance expenses over time. The inherently sturdier design of compression-ignition engines suggests that they may be more durable and have a longer life cycle between rebuilds. The higher efficiency of a diesel engine may also allow a higher rate of vapor consumption, thereby decreasing the running time required to evacuate a contamination site. Other important advantages that a CI engine may offer in this application are the capability to operate on a wide range of air/fuel ratios and the ability to use readily available JP-8 as a supplemental fuel instead of bottled gases. Use of a liquid fuel could also increase the length of run time between refuelings since a larger tank could be used, thereby reducing the labor costs associated with refueling.

Technical Approach: A small diesel engine was obtained from Air Force surplus inventory and equipped for operation as a pre-mixed vapor dual-fuel test platform. Propane was used as a surrogate gas to simulate the fuel vapors found in a typical well site. The engine was operated at various steady-state speed and load conditions, while the gas-to-air ratio in the intake air stream was incrementally increased. At each test point, the cylinder pressure was monitored for indications of potentially damaging knock, and parameters such as fuel and air consumption rates and engine temperatures were recorded.

Accomplishments: Data for three different load conditions at a constant engine speed of 2000 rpm were recorded. The data show that the basic concept of burning fuel vapors in a diesel engine by premixing them with the intake air is a viable concept. The data also show that the amount of JP-8 pilot fuel can be reduced with a corresponding increase in engine load. This experiment with propane demonstrated that the amount of necessary pilot fuel could be reduced to approximately 20% of the total fuel requirement under heavy loading conditions.

Military Impact: The results of this limited study show promise for the possibility of utilizing diesel engines in the task of removing and destroying fuel vapors from underground contamination sites. If the concept ultimately proves practicable through further investigation, it could potentially increase the effectiveness and reliability of engine-based ground vapor removal systems while simultaneously reducing the maintenance costs associated with them.

FOREWORD/ACKNOWLEDGMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, during the period October 2000 through May 2001 under Contract No. DAAE-07-99-C-L053. The work was funded by the U. S. Air Force Center for Environmental Excellence/Technology Transfer Division. The project was administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. Jerry Hansen (AFCEE/ERT) served as the project technical monitor.

STATEMENT OF ACCURACY

Fuel Flow	+/-	1% Full Scale (0 - 60 lbs/hr for JP-8 and 0-100 lbs/hr for Propane)
Temperature	+/-	2.16°F
Speed	+/-	5 RPM
Blower Pressure	+/-	1% Full Scale (0-100 psig max)

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ACRONYMS & ABBREVIATIONS

AFCEE	U. S. Air Force Center for Environmental Excellence
GC	Gas Chromatograph
CI	Compression Ignition
ERT	Environmnental Restoration Team
lbm	pound mass
LFE	Laminar Flow Element
SI	Spark Ignited
SwRI	Southwest Research Institute
TARDEC	Tank-Automotive Research Development and Engineering Center
TACOM	Tank-Automotive Armaments Command
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
TVH	Total Volatile Hydrocarbons

1.0 INTRODUCTION

Over a period of many years, leakage from underground storage tanks and spillage has created numerous subterranean contamination sites at U.S. Air Force bases worldwide. The first step in the currently employed practice for cleanup at these locations is to drill a well in the contaminated soil and extract liquid waste. Following removal of as much contaminant as possible in this manner, the next step in the clean-up process is to further remove residual contaminant in gaseous form as it evaporates from the saturated soil. For compounds such as solvents, the vapor is commonly forced through activated charcoal filtration units for cleanup, but this method is very costly in terms of the equipment and maintenance requirements. For less caustic compounds, such as jet fuel or gasoline, the vapors can be routed into the intake air of a running engine for combustion. This method has been shown to be a cost-effective alternative. The currently utilized version of this type of vapor extraction/destruction unit has a spark-ignited (SI) automobile engine that serves both as a vapor "pump" and a means of vapor destruction, with propane or natural gas serving as a supplemental fuel during startup and lean vapor conditions.

The continuous operation of an engine for this purpose can add up to significant maintenance expenses over time. In the interest of trying to obtain increased efficiency, durability and reliability in these engine-based extraction units, the question was put forth of whether it would be possible to use compression-ignition (CI) diesel engines in place of the SI engines now employed. The inherently sturdier design of CI engines suggests that they would be more durable and have a longer life cycle between rebuilds. The higher air utilization of a diesel engine may also allow a higher rate of vapor consumption, thereby decreasing the running time required to evacuate a contamination site. Another major advantage that a diesel engine could offer over a SI model is the ability to use readily available JP-8 as a supplemental fuel instead of bottled propane or natural gas. JP-8 would offer much greater convenience than propane since it can be stored in bulk on location and is available at all Air Force bases. Diesel engines are also capable of operating at a wider range of air to fuel ratios than SI engines. This characteristic could help reduce the sensitivity of the system to fluctuations in well vapor concentration.

2.0 OBJECTIVES

The objective of this project was to determine the feasibility of using a CI engine as a means of ground vapor extraction and destruction. The first priority was to determine if fuel vapors introduced into the engine via the intake air stream could be burned satisfactorily. An engine operated in this manner functions similarly to a dual-fuel natural gas/diesel unit, using liquid fuel as a pilot to ignite the gas-air mixture. A major concern with this concept is the possibility that fuel vapors pre-mixed with the intake air may be prone to detonation in a high compression diesel engine, therefore causing destructive knock. Another concern is whether the engine will run properly without using an excessive amount of supplemental liquid fuel, which then reduces the vapor extraction capability and overall efficiency of the system. Therefore, the main focus of this initial test phase was on combustion performance and pilot fuel requirements versus gaseous fuel consumption.

3.0 APPROACH

A portable aircraft cabin pressurization unit was provided by the Air Force and served as the test platform for this experiment. The unit consists of a small displacement, air-cooled diesel engine coupled to a roots-type air blower and an operator console for monitoring and regulating engine speed, blower air pressure and air flow. The blower was utilized as a means of providing a variable engine load, with the amount of load dependent on blower output pressure.

The basic configuration for pre-mixed vapor testing is shown in Figure 1. Gas flow rate is controlled by a manually operated needle valve mounted on the unit's control console. The gas is then combined with the intake airstream via a mixing ring before entering the intake manifold. JP-8 pilot fuel flow is regulated by the engine rack position control located on the operator console of the pressurization unit.

Upon delivery of the pressurization unit, an initial inspection revealed that the roots blower was seized due to oxidation of the rotors and case, rendering the unit inoperable. The blower was removed, disassembled and restored to operating condition. The Hatz engine was found to be in excellent working order following repair of the blower. Another

significant repair was necessary during initial shakedown runs when bolts joining the engine flywheel and blower drive coupling failed. Replacement parts were obtained from a spare pressurization unit and modified to better withstand the stresses encountered in the drivetrain. Testing was then able to resume without further incident.

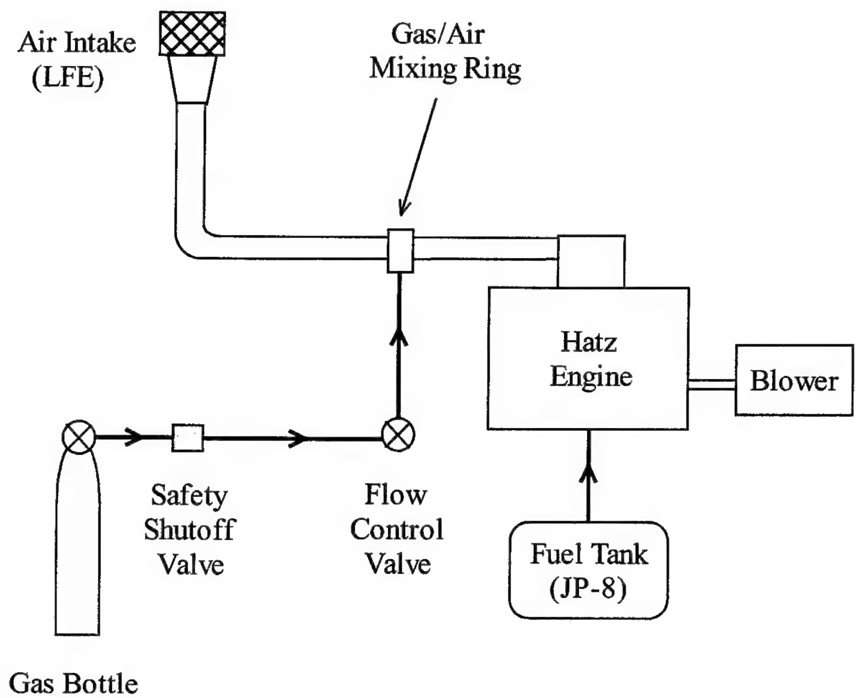

Figure 1. Pre-Mixed Vapor Test Configuration

3.1 Engine Installation

The engine utilized in the experiment was an air-cooled, normally aspirated Hatz model 4M40L. Specifications for this engine are listed in Table1.

Table 1. Test Engine Specification for Hatz 4M40L Diesel	
Engine Type	Four Cycle
Number of Cylinders	4
Bore/Stroke (mm)	102/105
Displacement (cc)	3432
Compression Ratio	18:1
Fuel Injector type	Mechanical

Figure 2 shows the Hatz engine/compressor unit installation in the test cell. Adjustment of engine speed, propane flow and blower pressure for the desired test conditions was accomplished from the operator console located on the back of the unit. The main parameters monitored included engine speed, intake air flow, propane and JP-8 fuel flows, blower pressure, and air, fuel, exhaust and oil temperatures. Intake air mass flow measurement was accomplished with the use of a laminar flow element (LFE), visible at the top of the photo in Figure 2. JP-8 and propane fuel mass flows were measured by two Micromotion units mounted on an isolated stand. Data was monitored with a Hewlitt-Packard PC based acquisition system that provides an averaged value for each parameter based on a number of consecutive samples specified by the operator.

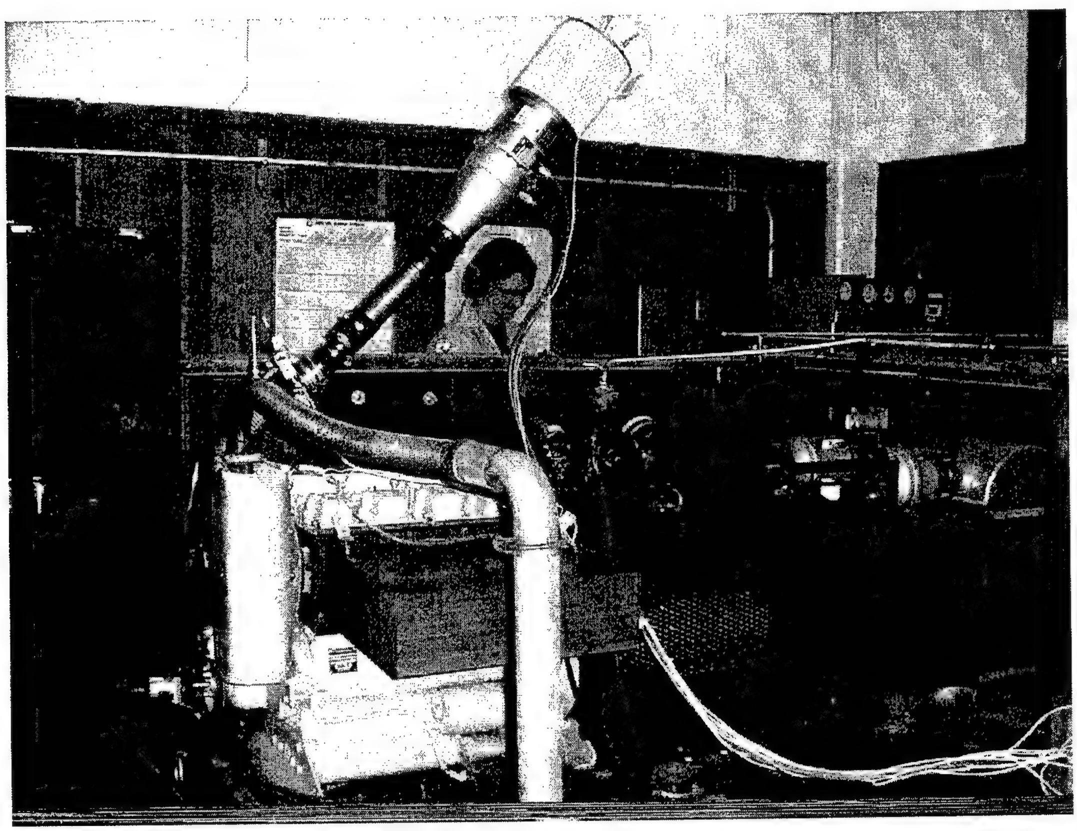

Figure 2. Hatz Engine/Compressor Unit Installation

3.2 Well Vapor Composition

To gain some knowledge of the hydrocarbon composition of vapors present in a typical fuel contamination site, a visit was made to Kelley Air Force Base, San Antonio, TX, to find a well from which samples could be drawn. A candidate well was located near a former refueling station, and samples were collected in evacuated stainless steel vessels using a portable peristaltic pump and tubing. Subsequent gas chromatograph (GC) analysis of the samples revealed the general volumetric composition of the vapor to be approximately 25% methane, 2% other assorted hydrocarbons, and 15% carbon dioxide, with the remainder undetermined but possibly air (Focus of the GC analysis was on isolating the hydrocarbon species.) Since methane is not present in military vehicle fuels, and considering the presence of a substantial quantity of CO_2, it was assumed that the large concentration of these gases was a product of degradation and would eventually dissipate during evacuation of vapors from the well. Therefore, the main compounds of interest would be the remaining 2% of assorted hydrocarbons, and these are the compounds that were simulated with a surrogate gas during engine tests. Hydrocarbons isolated from the well samples were predominantly C_5, with C_4 and C_6 compounds common, and some C_7 compounds also present. A copy of the GC analysis results can be found in Appendix C. The most readily available industrial gases that come closest to these carbon numbers are butane (C_4H_{10}) and propane (C_3H_8). These gases would make convenient surrogates for simulating the vapors found in the well site.

4.0 TEST PROCEDURE

The basic test procedure was to operate the engine at various steady-state speed and load conditions, while monitoring cylinder pressure and fuel consumption rates as the percentage of gas in the intake airstream was incrementally increased. If a change in engine set speed occurred upon the addition of gas, it was manually adjusted back to the desired set point by adjusting the liquid fuel flow rate via the engine rack control and then allowing the engine to stabilize. Cylinder pressure traces were recorded using a digital oscilloscope, with the objective being to maximize the quantity of gas that could be consumed without incurring excessive knock.

The engine was run according to the test matrix shown in Table 2. Each test condition consisted of a specific load and engine speed. At each test condition, the pilot fuel mass fraction of total fuel flow was varied in order to achieve seven different target test points. The test points are defined by the following code:

A. 100% pilot fuel
B. Balance gas and pilot fuel to match flow rate of point A
C. 80% pilot fuel
D. 60% pilot fuel
E. 40% pilot fuel
F. 20% pilot fuel
G. Minimize pilot fuel

An engine speed of 2000 rpm was chosen for the first series of tests in this initial feasibility study because it is near the peak torque point for the Hatz engine and is the approximate speed at which the SI engines are run in vapor extraction units currently used by the Air Force, therefore allowing for better comparison of performance data.

Table 2. Test Matrix

Test Condition	Engine RPM	Loading Condition	Blower Pressure	Test Pt. Sequence
1	2000	Light	2 psig	A-G, A
2	2000	Intermediate	8 psig	A-G, A
3	2000	Heavy	11 psig	A-G, A

The blower pressures chosen for the three test conditions were selected based on manufacturer data correlating blower pressure to engine power requirements. Following the attainment of each test point, the cylinder pressure trace data was recorded before moving on to the next point.

5.0 RESULTS

Data resulting from the test matrix of Table 2 can be found in Appendix A. A review of the fuel flow and exhaust temperature data reveals a trend showing an apparent improvement in combustion of the propane gas as the engine is more heavily loaded by the blower. For each test condition, there is a point at which total fuel flow begins to increase significantly from that of the 100% JP-8 baseline run. This point also corresponds to a rise in the exhaust gas temperature, indicating that combustion of the propane is continuing in the exhaust stream as the gas concentration becomes more than what the engine can effectively burn on the power stroke. The propane percentage of the total fuel flow at which this occurs can be seen to rise as the blower pressure is increased, thereby indicating better combustion of the propane at higher loading conditions.

The effect that increasing engine load has on propane combustion is illustrated by the curves of Figures 3 and 4. At a light load such as Test Condition 1, total fuel flow and exhaust temperature can be seen to start rising even as the pilot fuel quantity is initially reduced to 80%. Therefore, at this light loading condition the combustion of the propane appears to be very poor. The fact that the engine was not efficiently burning the propane at light load conditions was also noticeable by intensified shaking and vibration when the propane flow was subsequently increased. Looking at the fuel flow and exhaust temperature data for Test Condition 2 (intermediate load), propane combustion appears to be good for approximately 50% or more pilot fuel. At the heaviest load of Test Condition 3, the results are seen to further improve as a decrease in combustion performance is not indicated until the pilot fuel quantity is reduced to nearly 20%. In fact, at this load condition the total fuel flow and exhaust temperature are slightly lower than those of the 100% pilot case before propane is added.

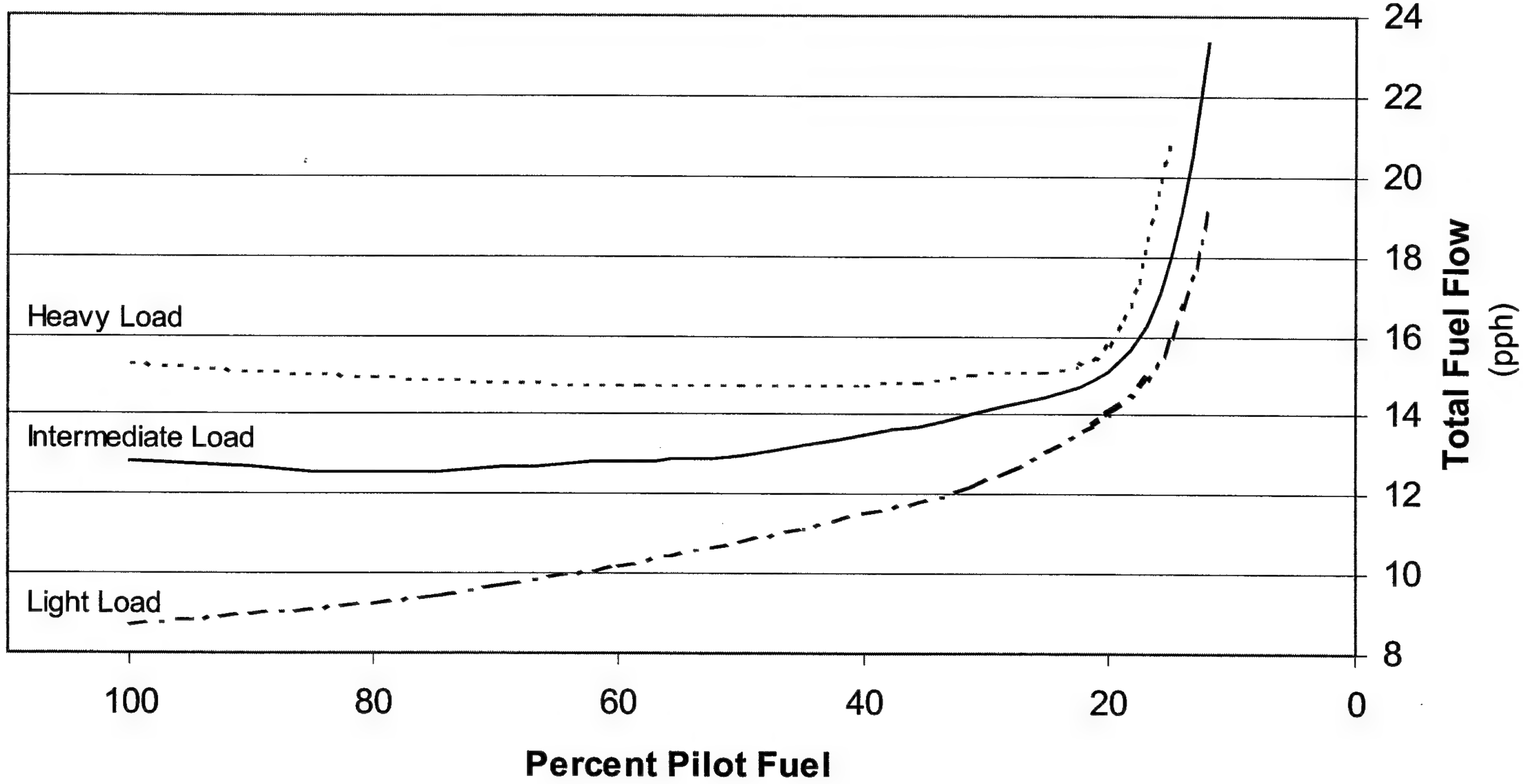

Figure 3. Total Fuel Consumption vs. JP-8 Pilot quantity as a Function of Engine Load at 2000 RPM

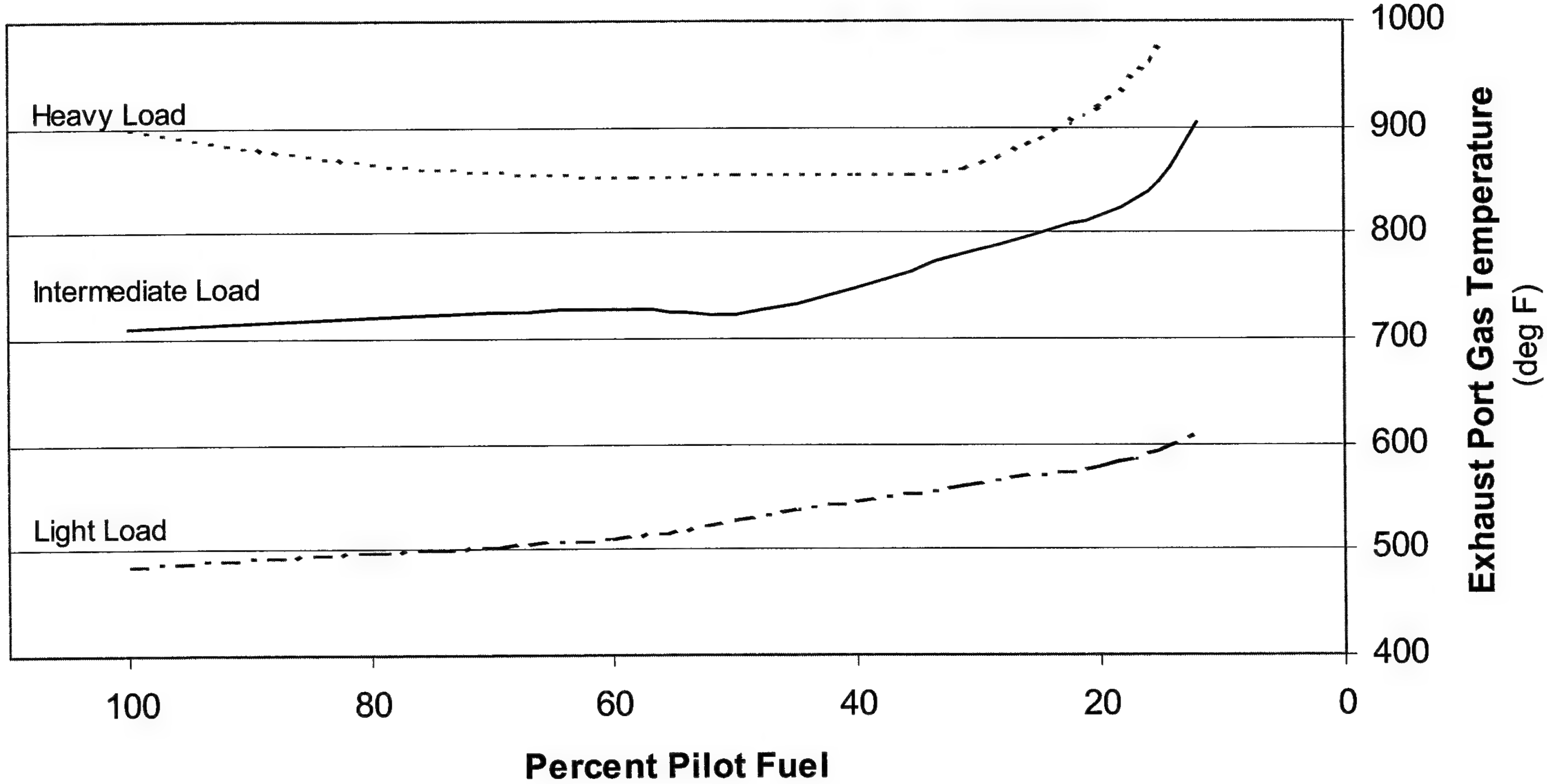

Figure 4. Exhaust Port Gas Temperature vs. JP-8 Pilot Quantity as a Function of Engine Load at 2000 RPM

Figure 5 illustrates the changes in JP-8 and propane fuel flow for each test condition as the pilot fuel quantity varies. Also indicated on this graph are the points of maximum propane flow that can be effectively utilized by the engine at each load condition, based on the previously discussed total fuel flow and exhaust temperature data. It can be seen that the highest loading condition produces the greatest effective propane consumption with the least amount of pilot fuel. At approximately 20% pilot fuel, the engine is able to consume over 12 lbm/hr of gaseous propane while using 3 lbm/hr of liquid JP-8 fuel. At this rate, the Hatz engine could operate for approximately 60 hours on the 27-gallon capacity of the pressurization unit's fuel tank and consume nearly 290 lbm/day of gaseous hydrocarbons (assumes JP-8 density of 6.7 lbm/gal.)

The percentage of propane present in the engine intake airstream may be compared to the Total Volatile Hydrocarbon (TVH) concentration of typical contamination site well vapors if the remaining balance of the well vapor is assumed to be air. This allows the engine's gaseous fuel requirements for a desired vapor extraction level to be compared to the supply available at various well sites. For example, from the averaged data of Appendix A, the propane concentration at Test Condition 3 and 20% pilot fuel can be found to be approximately .034, or 3.4% by mass. Since propane is about 57% heavier than air per unit volume at ambient temperature and pressure, the corresponding volume fraction will be lower for a given mass fraction. For this case, a .034 propane mass fraction is approximately equal to a .023 volume fraction (Calculations, Appendix D). Likewise, the propane volume fraction for Condition 3 at 40% pilot fuel is seen to be .019. This value compares favorably to the vapor sample obtained from a well site at Kelly Air Force Base (Appendix A) that was found to be approximately 1.7% TVH by volume. However, if additional atmospheric air must be inducted for proper combustion of the fuel-air mixture, then the TVH/air ratio would be lower and this comparison would not be valid.

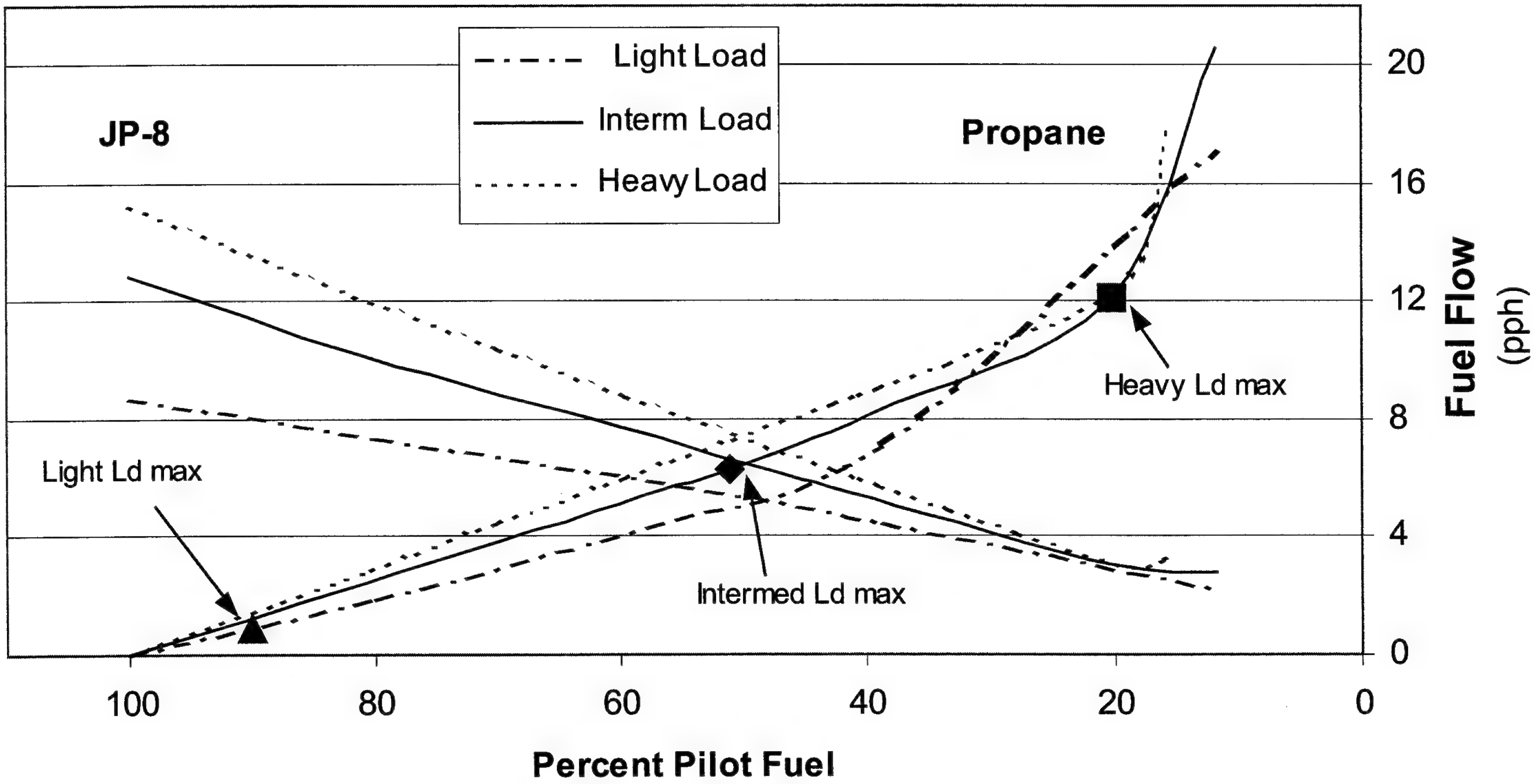

Figure 5. JP-8 Propane Fuel Consumption vs. Pilot Percentage as a Function of Engine Load

One of the main concerns addressed at the beginning of this project was whether severe detonation knock would be encountered when fuel vapor was pre-mixed with the intake air. The cylinder pressure traces for Test Condition 2, illustrated in Figures 6 and 7, show that the combustion process is slightly more erratic with the addition of propane gas, but there are no severe pre- or post-ignition spikes to indicate serious detonation problems. As the percentage of propane in the total fuel flow increases, the peak cylinder pressure of the compression and power strokes can be seen to decrease accordingly. As was also observed from the fuel flow and exhaust temperature data, the noted change in power stroke cylinder pressure indicates a substantial decrease in combustion performance as the amount of pilot fuel falls below 50% at this particular load condition. The reduction in compression stroke peak pressure can possibly be attributed to a change in compressibility characteristics of the inlet air/gas charge as an increasingly larger portion of the intake air is replaced by propane. As the percentage of propane rises, the specific heat ratio of the mixture decreases, causing a subsequent lowering of the peak pressure realized. Also indicated by the pressure traces is a lengthening of delay in the start of ignition as the percentage of propane is elevated. The ignition delay at this test condition appears to be minor until the pilot fuel quantity is lessened to 50%, at which point there is 2 to 3 crankshaft degrees delay from that of the 100% JP-8 base run.

5.1 Problems Encountered

Cylinder pressure trace data was not properly recorded for most of Test Conditions 1 and 3. However, the pressure traces for test points A-E at Condition 2 were successfully captured and provide a good picture of how the addition of propane to the air stream affects the engine combustion process in general.

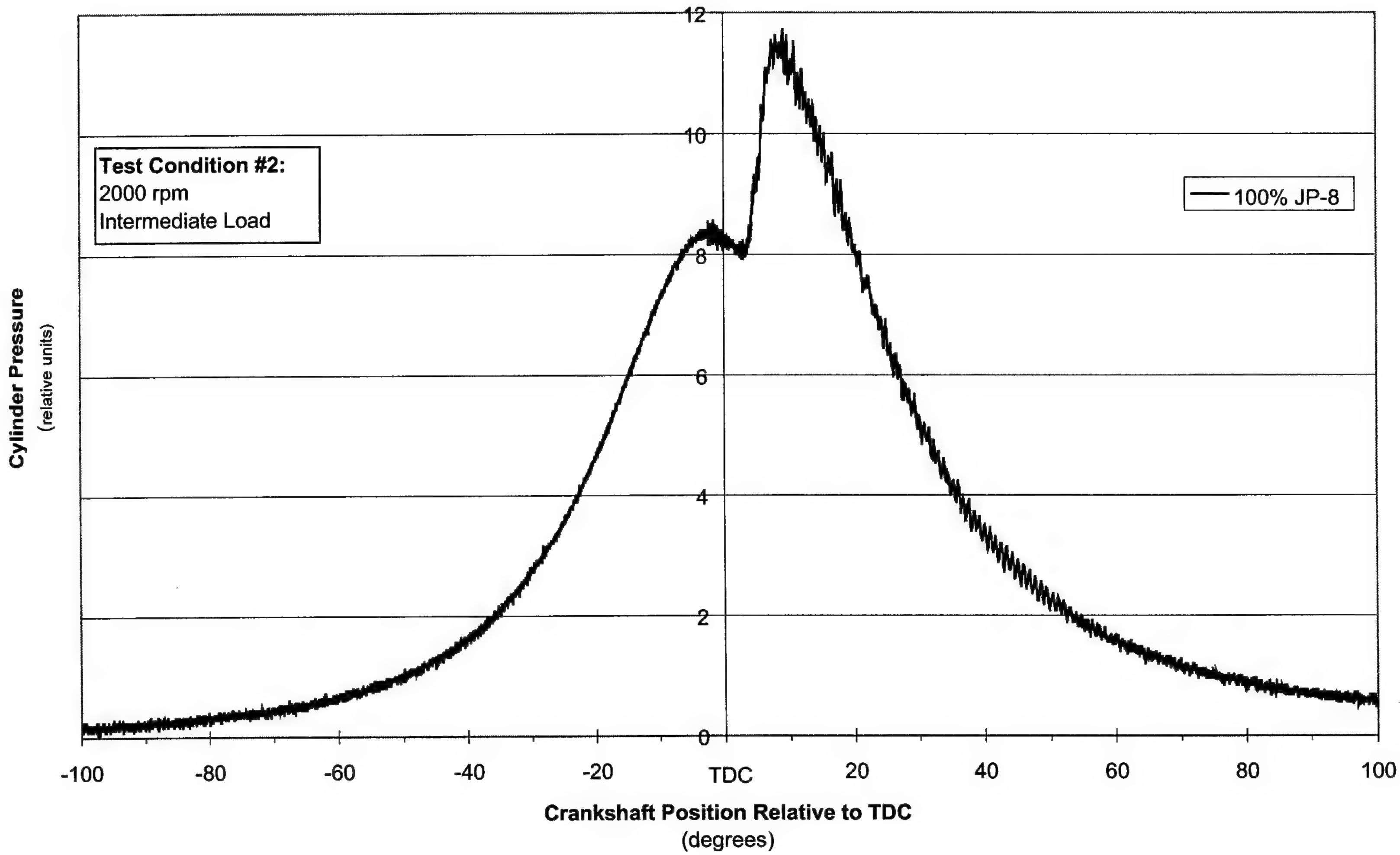

Figure 6. Hatz Engine Baseline Cylinder Pressure Using JP-8 Only

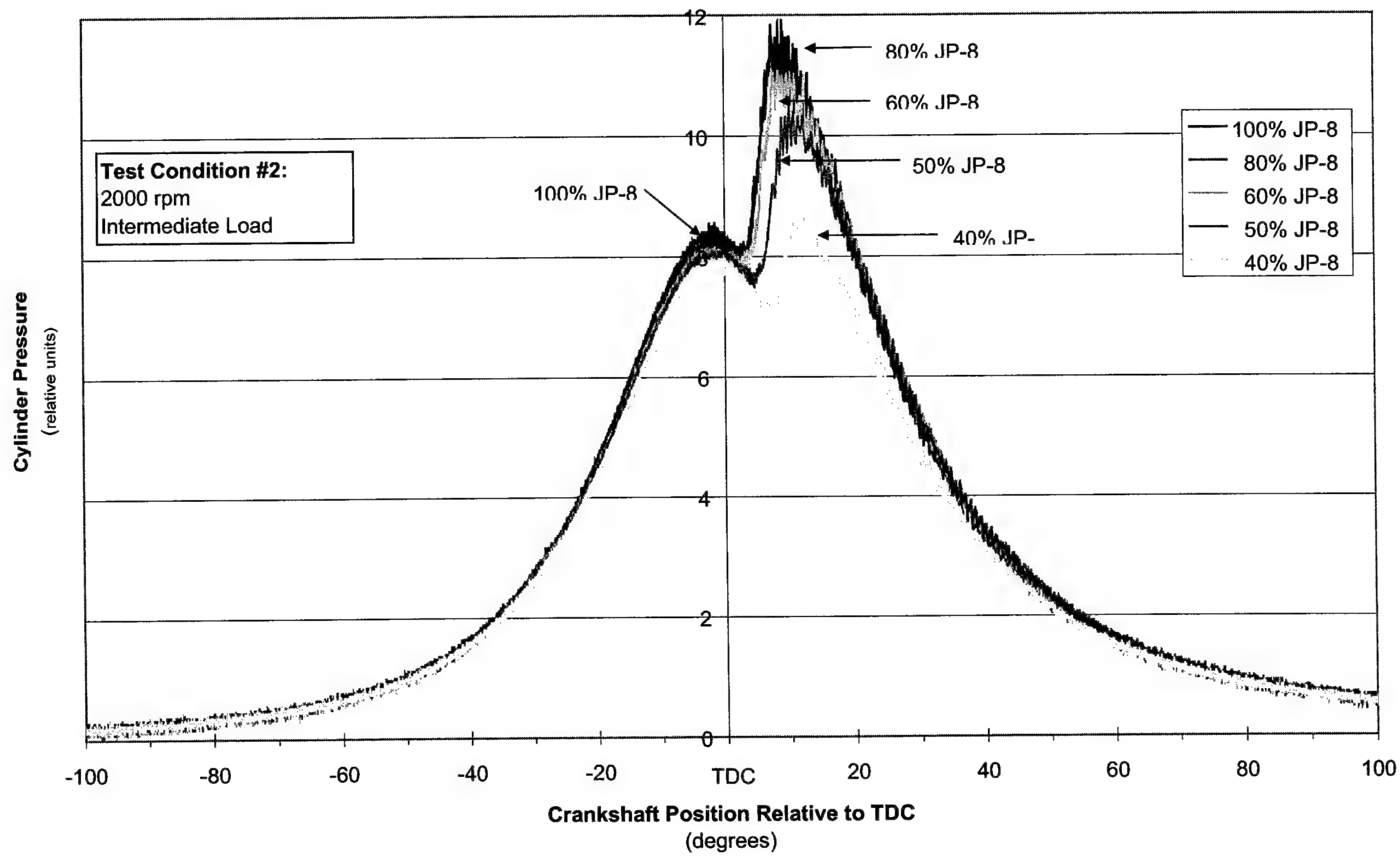

Figure 7. Hatz Engine Cylinder Pressure at Various JP-8/Propane Mixtures

6.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this initial effort appear to be promising. The data show that the basic concept of burning pre-mixed gaseous fuel vapors in this diesel engine using liquid fuel as an ignition pilot is indeed feasible. It has also been shown that the combustion of a gaseous fuel increases as engine load increases. The current results show that under significant loading conditions, the pilot fuel amount can be reduced to approximately 20% of the total fuel requirement, assuming the fuel vapors are highly enough concentrated to sustain engine operation.

It must be noted that the results shown in this study are far from conclusive. The propane gas used in the experiment is of a lower molecular weight and carbon number (C_3) than that of the actual well vapors (near C_5 on average) and it is unknown whether the same results would be obtained with a heavier gas. Therefore, using the knowledge and results obtained from this first phase of testing, considerable advancement could be made toward evaluation of the true potential of vapor extraction and destruction using a diesel engine. It is recommended that a second phase of testing be undertaken, with focus placed on the following aspects.

- Installation of the test engine on a dynamometer to facilitate stricter control of engine load.
- A comparison study using butane to examine the combustion of a heavier gas.
- The feasibility of collecting and bottling actual well vapors for laboratory engine testing.
- Exhaust emissions analysis, including evaluation of hydrocarbons, CO and CO_2 concentrations.
- Mapping of quantitative gas consumption rates and destruction efficiencies.
- A throttling experiment to examine the effects of engine intake air restriction, as would be seen when installed at a well site.

APPENDIX A

RAW DATA

Hatz Vapor Burn Test Data
Project # 03-03227-07.001

Test No.	Test Condition	Date	Time	Engine Speed (rpm)	Blower Press (psig)	Test Point	% Pilot	JP-8 Fuel Flow (lbs/hr)	Propane Flow (lbs/hr)	Total Fuel Flow (lbs/hr)
1	1	03/14/01	21:37:06	2002	2.0	A_start	100	8.77	0	8.77
			21:38:51	2001	2.0	A_start	100	8.71	0	8.71
			22:43:45	2001	2.0	C	83.50	7.39	1.46	8.85
			22:45:00	2002	2.0	C	76.59	7.39	2.26	9.65
			22:45:58	2001	2.0	C	80.05	7.41	1.85	9.26
			23:23:31	2004	2.0	D	56.40	5.90	4.56	10.46
			23:24:46	2004	1.9	D	56.43	5.76	4.45	10.21
			23:33:48	2002	2.0	D	59.27	5.88	4.04	9.92
			23:34:46	2003	2.0	D	57.12	5.93	4.46	10.39
			23:36:45	2003	2.0	D	59.47	6.04	4.12	10.16
			23:52:07	2004	2.0	E	38.13	4.43	7.18	11.61
			23:53:23	2003	2.0	E	38.31	4.47	7.2	11.67
			23:54:32	2004	2.0	E	40.32	4.53	6.71	11.24
			23:59:36	2004	2.0	E	38.32	4.44	7.15	11.59
		03/15/01	0:26:59	2008	2.1	G	12.80	2.38	16.23	18.61
			0:28:46	2011	2.1	G	10.70	2.19	18.25	20.44
			0:30:33	2012	2.1	G	11.55	2.16	16.57	18.73
			0:38:36	2003	2.0	A_end	100	8.72	0	8.72
			0:40:03	2003	2.0	A_end	100	8.72	0	8.72
	2		0:51:37	1999	8.0	A_start	100	12.82	0	12.82
			0:52:59	2000	8.0	A_start	100	12.80	0	12.80
			1:04:27	1998	8.0	B	49.82	6.45	6.49	12.94
			1:27:57	2002	8.0	C	80.42	10.13	2.47	12.60
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			2:15:43	2004	8.0	E	39.82	5.34	8.07	13.41
			2:16:45	2005	8.0	E	39.29	5.34	8.26	13.60
			2:42:42	2005	8.0	F	20.42	3.08	12.00	15.08
			2:47:27	2009	8.1	G	12.29	2.83	20.16	22.99
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			2:59:06	2002	8.0	A_end	100	12.75	0	12.75

Test No.	Test Condition	Date	Time	Engine Speed (rpm)	Blower Press (psig)	Test Point	% Pilot	JP-8 Fuel Flow (lbs/hr)	Propane Flow (lbs/hr)	Total Fuel Flow (lbs/hr)
	3		3:20:35	2002	11.0	A_start	100	15.27	0	15.27
			3:22:03	2001	11.0	A_start	100	15.32	0	15.32
			3:32:40	2002	11.0	B	30.95	4.62	10.30	14.92
			3:34:05	2002	11.0	B	30.63	4.61	10.43	15.04
			3:44:33	2003	11.0	C	80.88	12.03	2.84	14.87
			3:45:25	2003	11.0	C	80.17	12.02	2.97	14.99
			3:58:01	2003	11.0	D	58.81	8.77	6.14	14.91
			3:58:53	2002	11.0	D	59.93	8.81	5.89	14.70
			4:00:01	2002	11.0	D	59.98	8.85	5.90	14.75
			4:14:22	2002	11.0	E	40.53	6.01	8.81	14.82
			4:15:24	2003	11.0	E	40.80	6.02	8.74	14.76
			4:38:16	2005	11.1	F	18.58	2.91	12.73	15.64
			4:41:14	2005	11.1	F	18.77	2.99	12.95	15.94
			4:52:10	2017	11.1	G	15.70	3.35	18.00	21.35
			4:53:22	2016	11.1	G	15.46	3.32	18.14	21.46
			5:03:24	2005	11.0	A_end	100	15.29	0	15.29
			5:05:55	2002	11.0	A_end	100	15.27	0	15.27

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Test No.	Test Condition	A/F Ratio (total fuel) (X:1)	Air Flow dry mass (lbs/hr)	Air Flow volume (acfm)	Prop/Air Ratio (X:1)	JP-8 Temp (^oF)	Propane Temp (^oF)	LFE Air In Temp (^oF)	Intake Man. Air Temp (^oF)
1	1	44.86	393.6	94.3	0	107.0	87.3	86.7	91.9
		44.68	389.4	93.3	0	106.7	87.1	86.8	91.3
		44.19	390.8	93.8	0.004	108.8	89.6	87.4	92.6
		40.34	389.4	93.5	0.006	109.1	89.6	87.4	92.8
		42.10	389.9	93.6	0.005	109.0	89.7	87.3	92.8
		37.27	389.9	93.6	0.012	109.5	89.7	87.4	92.6
		38.13	389.2	93.5	0.011	109.4	89.7	87.6	92.5
		39.24	389.6	93.6	0.010	109.5	90.0	87.8	92.8
		37.44	389.0	93.5	0.011	109.5	89.9	87.7	92.7
		38.37	389.5	93.6	0.011	109.5	90.0	87.8	92.9
		33.46	388.4	93.3	0.018	109.9	89.9	87.6	93.0
		33.22	388.0	93.2	0.019	110.1	89.7	87.6	92.8
		34.48	387.5	93.2	0.017	110.0	89.8	87.9	92.9
		33.55	389.0	93.5	0.018	110.2	89.7	87.9	93.1
		20.38	379.3	91.3	0.043	110.3	89.0	88.2	93.5
		18.37	375.5	90.4	0.049	110.7	88.7	88.6	93.7
		20.07	376.2	90.6	0.044	111.3	88.5	88.6	93.9
		44.75	390.2	94.0	0	111.5	89.3	88.8	93.8
		44.72	390.1	93.9	0	111.1	89.3	88.5	93.8
	2	29.78	381.8	93.0	0	112.6	90.1	95.2	98.1
		29.79	381.2	93.0	0	113.1	90.4	95.8	98.6
		29.00	375.3	92.2	0.017	117.9	96.9	99.8	101.3
		29.78	375.3	92.1	0.007	121.0	99.1	99.3	103.1
		29.95	375.4	92.2	0.006	121.2	99.2	99.3	103.3
		29.37	373.6	91.8	0.014	122.6	101.4	99.8	103.8
		28.72	372.9	91.8	0.014	122.6	101.3	100.9	104.3
		27.77	372.4	91.8	0.022	123.8	101.9	101.3	104.6
		27.33	371.7	91.7	0.022	123.8	102.0	101.4	104.9
		24.50	369.5	91.3	0.032	126.5	101.7	102.7	106.0
		15.71	361.0	89.3	0.056	126.7	101.6	103.4	106.0
		15.28	361.6	89.4	0.058	126.7	101.1	103.0	106.3
		29.37	374.6	92.3	0	125.7	99.6	101.3	105.6

Test No.	Test Condition	A/F Ratio (total fuel) (X:1)	Air Flow dry mass (lbs/hr)	Air Flow volume (acfm)	Prop/Air Ratio (X:1)	JP-8 Temp (^oF)	Propane Temp (^oF)	LFE Air In Temp (^oF)	Intake Man. Air Temp (^oF)
.	3	24.13	368.3	91.8	0	126.5	99.7	107.7	109.5
		24.15	370.0	92.2	0	126.9	100.0	107.7	109.8
		24.48	365.2	91.1	0.028	129.9	107.3	108.1	110.6
		24.29	365.3	91.1	0.029	130.1	107.5	107.8	110.3
		24.77	368.4	92.0	0.008	130.0	105.2	108.5	110.6
		24.45	366.5	91.5	0.008	130.0	105.1	108.6	110.6
		24.54	365.8	91.4	0.017	130.8	107.6	108.8	111.3
		24.86	365.2	91.2	0.016	131.0	107.5	108.8	111.0
		24.82	366.1	91.4	0.016	130.9	107.6	108.4	110.9
		24.66	365.4	91.2	0.024	131.7	107.8	108.5	110.5
		24.76	365.5	91.2	0.024	131.5	107.8	108.6	110.7
		23.25	363.5	90.4	0.035	131.5	106.3	108.0	109.7
		22.96	366.1	90.6	0.035	130.0	104.1	104.1	106.7
		16.91	361.2	88.5	0.050	123.9	93.4	98.0	97.9
		17.06	366.1	89.5	0.050	123.5	92.8	97.2	97.5
		24.74	378.1	92.0	0	118.0	86.9	94.6	94.3
		24.66	376.5	91.9	0	116.7	86.6	95.9	95.1

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Test No.	Test Condition	Oil Sump Temp (°F)	Cooling Air In (°F)	Cooling Air Out (°F)	Port Exh. Temp (°F)	Stack Exh. Temp (°F)	Amb. Air Temp (°F)	Amb. Air Rel. Hum. (percent)
1	1	195.4	92.5	149.0	486.2	466.5	66.4	67.4
		195.9	90.8	149.6	485.6	466.3	65.6	69.5
		196.4	93.6	150.7	497.6	475.5	64.9	71.5
		196.3	94.4	150.7	498.0	474.5	64.9	71.5
		196.7	93.7	150.6	497.6	474.5	64.9	71.5
		194.6	92.6	147.6	514.3	488.9	64.3	72.3
		195.0	94.8	147.7	512.0	487.8	64.3	72.3
		194.6	95.0	148.7	510.7	486.1	64.5	72.2
		194.8	94.2	148.5	512.5	486.9	64.5	72.2
		195.0	94.2	148.8	510.3	486.6	64.5	72.2
		193.8	93.5	145.0	546.2	519.6	64.3	72.3
		193.6	94.1	145.0	546.7	519.1	64.3	72.3
		193.7	94.7	145.1	547.2	519.7	64.3	72.3
		193.4	93.3	144.9	544.5	517.1	64.3	72.3
		194.8	94.8	161.2	608.9	574.9	64.0	72.9
		197.5	93.8	163.0	612.0	575.9	64.0	72.9
		197.2	94.7	163.7	613.3	579.9	64.0	72.9
		199.3	95.4	153.7	487.4	467.8	64.0	72.9
		199.5	97.7	153.5	487.1	466.8	64.0	72.9
	2	208.8	97.7	168.8	710.5	671.1	64.0	72.9
		210.5	97.3	169.6	711.4	672.7	64.0	72.9
		214.6	103.7	167.6	723.9	687.4	64.0	72.9
		221.2	101.1	174.9	720.5	680.7	64.0	72.9
		221.5	102.5	175.5	720.0	680.9	64.0	72.9
		221.5	105.8	172.9	726.4	684.6	64.0	72.9
		221.5	95.3	172.2	726.7	685.0	64.0	74.3
		219.8	105.5	169.8	747.8	706.9	64.0	74.3
		219.8	100.7	169.7	748.0	706.8	64.0	74.3
		221.7	100.0	171.7	817.1	765.9	64.2	71.5
		222.3	108.0	183.5	904.3	818.6	64.2	71.5
		223.1	102.8	186.0	901.7	819.9	64.2	71.5
		227.5	106.1	181.2	734.4	697.0	64.2	71.5

Test No.	Test Condition	Oil Sump Temp (°F)	Cooling Air In (°F)	Cooling Air Out (°F)	Port Exh. Temp (°F)	Stack Exh. Temp (°F)	Amb. Air Temp (°F)	Amb. Air Rel. Hum. (percent)
	3	235.7	98.1	189.8	899.3	848.8	63.9	71.8
		236.5	106.6	190.6	899.7	848.6	63.9	71.8
		235.8	104.4	179.9	861.0	812.1	63.8	70.9
		235.2	106.1	180.0	862.0	812.2	63.8	70.9
		238.2	107.8	190.3	867.0	817.1	63.8	71.1
		238.3	102.7	189.5	867.3	817.3	63.8	71.1
		238.8	105.4	188.6	853.9	802.8	63.7	71.1
		239.0	102.9	188.0	854.5	803.9	63.7	71.1
		238.6	105.7	188.3	854.2	803.9	63.7	71.1
		236.4	104.4	182.2	857.3	804.5	63.3	71.4
		236.2	105.4	182.2	857.2	804.4	63.3	71.4
		234.1	105.5	184.6	917.5	861.5	62.5	72.4
		232.7	102.9	181.9	918.7	861.3	62.5	72.4
		233.8	95.0	185.3	972.0	899.5	60.0	78.0
		234.1	94.1	184.8	971.9	899.7	60.0	78.0
		230.4	94.0	177.1	863.3	814.1	60.0	78.0
		229.5	93.4	177.3	859.2	811.1	60.0	78.0

APPENDIX B
AVERAGED RAW DATA

Hatz Vapor Burn Averaged Test Data
Project # 03-03227-07.001

Test No.	Test Condition	Engine Speed (rpm)	Blower Press (psig)	Test Point	% Pilot	JP-8 Fuel Flow (lbs/hr)	Propane Flow (lbs/hr)	Total Fuel Flow (lbs/hr)	A/F Ratio (total fuel) (X:1)	Air Flow dry mass (lbs/hr)	Air Flow volume (acfm)	Prop/Air Ratio (X:1)	JP-8 Temp (°F)	Propane Temp (°F)	LFE Air In Temp (°F)
1	1	2002	2.0	A_start	100	8.74	0	8.74	44.77	391.5	93.8	0	106.9	87.2	86.8
		2001	2.0	C	80.05	7.40	1.86	9.25	42.21	390.0	93.6	0.005	109.0	89.6	87.4
		2003	2.0	D	57.74	5.90	4.33	10.23	38.09	389.4	93.6	0.011	109.5	89.9	87.7
		2004	2.0	E	38.77	4.47	7.06	11.53	33.68	388.2	93.3	0.018	110.1	89.8	87.8
		2010	2.1	G	11.68	2.24	17.02	19.26	19.61	377.0	90.8	0.045	110.8	88.7	88.5
		2003	2.0	A_end	100	8.72	0	8.72	44.74	390.2	94.0	0	111.3	89.3	88.7
	2	2000	8.0	A_start	100	12.81	0	12.81	29.79	381.5	93.0	0	112.9	90.3	95.5
		1998	8.0	B	49.82	6.45	6.49	12.94	29.00	375.3	92.2	0.017	117.9	96.9	99.8
		2001	8.0	C	80.77	10.15	2.42	12.57	29.87	375.4	92.2	0.006	121.1	99.2	99.3
		2001	8.0	D	60.06	7.72	5.14	12.85	29.05	373.3	91.8	0.014	122.6	101.4	100.4
		2005	8.0	E	39.56	5.34	8.17	13.51	27.55	372.1	91.8	0.022	123.8	102.0	101.4
		2005	8.0	F	20.42	3.08	12.00	15.08	24.50	369.5	91.3	0.032	126.5	101.7	102.7
		2009	8.1	G	11.81	2.76	20.58	23.33	15.50	361.3	89.4	0.057	126.7	101.4	103.2
		2002	8.0	A_end	100	12.75	0	12.75	29.37	374.6	92.3	0	125.7	99.6	101.3
	3	2002	11.0	A_start	100	15.30	0	15.30	24.14	369.2	92.0	0	126.7	99.9	107.7
		2002	11.0	B	30.79	4.62	10.37	14.98	24.39	365.3	91.1	0.028	130.0	107.4	108.0
		2003	11.0	C	80.53	12.03	2.91	14.93	24.61	367.5	91.8	0.008	130.0	105.2	108.6
		2002	11.0	D	59.57	8.81	5.98	14.79	24.74	365.7	91.3	0.016	130.9	107.6	108.7
		2003	11.0	E	40.67	6.02	8.78	14.79	24.71	365.5	91.2	0.024	131.6	107.8	108.6
		2005	11.1	F	18.68	2.95	12.84	15.79	23.11	364.8	90.5	0.035	130.8	105.2	106.1
		2017	11.1	G	15.58	3.34	18.07	21.41	16.99	363.7	89.0	0.050	123.7	93.1	97.6
		2004	11.0	A_end	100	15.28	0	15.28	24.70	377.3	92.0	0	117.4	86.8	95.3

Hatz Vapor Burn Averaged Test Data
Project # 03-03227-07.001

Test No.	Test Condition	Engine Speed (rpm)	Blower Press (psig)	Test Point	% Pilot	Intake Man. Air Temp (°F)	Oil Sump Temp (°F)	Cooling Air In (°F)	Cooling Air Out (°F)	Port Exh. Temp (°F)	Stack Exh. Temp (°F)	Amb. Air Temp (°F)	Amb. Air Rel. Hum. (percent)	Prop % of Intake Chg (by mass)	Prop % of Intake Chg (by volume)
1	1	2002	2.0	A_start	100	91.6	195.7	91.7	149.3	485.9	466.4	66.0	68.5	0	0
		2001	2.0	C	80.05	92.7	196.5	93.9	150.7	497.7	474.8	64.9	71.5	0.5	0.3
		2003	2.0	D	57.74	92.7	194.8	94.2	148.3	512.0	487.3	64.4	72.2	1.1	0.7
		2004	2.0	E	38.77	93.0	193.6	93.9	145.0	546.2	518.9	64.3	72.3	1.8	1.2
		2010	2.1	G	11.68	93.7	196.5	94.4	162.6	611.4	576.9	64.0	72.9	4.3	2.9
		2003	2.0	A_end	100	93.8	199.4	96.6	153.6	487.3	467.3	64.0	72.9	0	0
	2	2000	8.0	A_start	100	98.4	209.7	97.5	169.2	711.0	671.9	64.0	72.9	0	0
		1998	8.0	B	49.82	101.3	214.6	103.7	167.6	723.9	687.4	64.0	72.9	1.7	1.1
		2001	8.0	C	80.77	103.2	221.4	101.8	175.2	720.3	680.8	64.0	72.9	0.6	0.4
		2001	8.0	D	60.06	104.1	221.5	100.6	172.6	726.6	684.8	64.0	73.6	1.4	0.9
		2005	8.0	E	39.56	104.8	219.8	103.1	169.8	747.9	706.9	64.0	74.3	2.1	1.5
		2005	8.0	F	20.42	106.0	221.7	100.0	171.7	817.1	765.9	64.2	71.5	3.1	2.1
		2009	8.1	G	11.81	106.2	222.7	105.4	184.8	903.0	819.3	64.2	71.5	5.4	3.6
		2002	8.0	A_end	100	105.6	227.5	106.1	181.2	734.4	697.0	64.2	71.5	0	0
	3	2002	11.0	A_start	100	109.7	236.1	102.4	190.2	899.5	848.7	63.9	71.8	0	0
		2002	11.0	B	30.79	110.5	235.5	105.3	180.0	861.5	812.2	63.8	70.9	2.8	1.9
		2003	11.0	C	80.53	110.6	238.3	105.3	189.9	867.2	817.2	63.8	71.1	0.8	0.5
		2002	11.0	D	59.57	111.1	238.8	104.7	188.3	854.2	803.5	63.7	71.1	1.6	1.1
		2003	11.0	E	40.67	110.6	236.3	104.9	182.2	857.3	804.5	63.3	71.4	2.3	1.6
		2005	11.1	F	18.68	108.2	233.4	104.2	183.3	918.1	861.4	62.5	72.4	3.4	2.3
		2017	11.1	G	15.58	97.7	234.0	94.6	185.1	972.0	899.6	60.0	78.0	4.7	3.2
		2004	11.0	A_end	100	94.7	230.0	93.7	177.2	861.3	812.6	60.0	78.0	0	0

APPENDIX C

WELL-VAPOR ANALYSIS RESUTLTS

KELLY AFB WELL-VAPOR HYDROCARBON ANALYSIS RESULTS

COMPOUND	PPM		MWt
80 3MC5	2033.15		84.09
74 2MC5	1996.61		100.13
22 iC5	1618.72		72.09
158 23DMC5	1238.33		112.1
112 McyC5	1173.44		98.11
222 McyC6	1165.73		128.16
96 nC6	1114.91		100.13
30 nC5	1105.69		72.09
166 3MC6	787.35		112.1
64 23DMC4	772.49		86.11
136 cyC6	712.58		114.14
186 224TMC5	692.73		112.13
200 nC7	525.04		112.1
116 24DMC5	415.03		114.14
52 22DMC4	365.24		68.08
176 t12DMcyC5	270.79		114.14
130 Benzene	265.48		114.14
172 t13DMcyC5	214.99		112.1
174 c13DMcyC5	186.62		114.14
62 cyC5	178.87		86.11
40 2M2C4=	139.61		86.11
134 33DMC5+5M1C6:	126.11		112.1
250 24DMC6	119.10		126.14
326 2MC7	116.73		126.14
TOTAL	17335.34	**Avg Mol Wt**	98.36

For simplification purposes, this data shows only hydrocarbon compounds that comprised more than 1 mole percent of the original sample analysis results.
The analysis showed the sample to contain approximately 2% assorted HCs, 25% methane and 15% CO_2 with the remaining content undetermined, but possibly consisting of air.
(Focus of the GC analysis was on isolating the hydrocarbon species)
The methane and CO_2 are likely the result of degradation and would dissipate with time, therefore, they are not considered as part of the vapor composition for long term operating conditions.

APPENDIX D

CALCULATION & FUEL/GAS PROPERTIES

Appendix Calculations

	Avg Mass Flow	Mass Fract		Mol Wt	kmol/kg	Mol Fract	%Vol
Air	364.8	.966	÷	28.97	= .03334	.977	97.7
Propane	12.8	.034	÷	44.097	= .00077	.023	2.3
	377.6				.03411		

So, it can be seen that; %Vol Fraction Propane = %Mass Fraction Propane x .6765

Appendix Data

JP-8 lower heating value: 18,400 Btu/lbm

Propane lower heating value: 20,000 Btu/lbm